

# A Lithium Experiment as the Stringent Test of the Theory of Stellar Evolution.

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## Abstract

We show that a lithium experiment has a potential to confirm or reject the value 1.5% of the solar luminosity attributed to a CNO-cycle by the standard solar model and to prove that the difference between total energy release of the Sun and what is produced in a hydrogen sequence is really produced in CNO cycle. This will be the stringent test of the theory of stellar evolution and the termination of the long-standing goal – the neutrino spectroscopy of the interior of the Sun. At the present time one can see no other way to solve this task, it can be accomplished only with a lithium detector utilizing its high sensitivity to CNO-neutrinos and very high accuracy in the theoretical evaluation of the cross-section of neutrino capture by  ${}^7\text{Li}$ . The analyses shows that although a lithium detector is a radiochemical one, principally it is possible to find separately the fluxes of  ${}^{13}\text{N}$ - and  ${}^{15}\text{O}$ -neutrinos.

The primary goal of the solar neutrino experiment since the early phase of the research pioneered by Raymond Davis was first - to prove the thermonuclear nature of the energy generation in the interior of the Sun and second - to find the experimental evidence that the Sun shines by the pp-chain and not by the CNO cycle. Soon the goal was formulated [1] as a “Neutrino Spectroscopy of the Interior of the Sun” (NSIS). Since that time the copious experimental material was accumulated [2]. The field turned out to be very productive, the experiments not only provided the first direct evidence of the thermonuclear nature of the energy of the Sun, they discovered basically new properties of neutrinos – neutrino oscillations and measured its parameters:  $\Delta m^2$  and mixing angle [3]. The progress in this field is really very impressive. In a few years when a lithium project will be ready for the realization as a full-scale experiment, a lot more will be accomplished: basically all neutrino fluxes of hydrogen-sequence reactions and also the neutrino oscillation parameters will be measured with good accuracy. The only thing left will be presumably the neutrinos of CNO-cycle (at least now one can see no way how they could be detected apart from a lithium experiment). Figure 1 shows CNO reactions in schematic form [6].

At the present time only an upper limit of 7.3% was set [4] to the fraction of energy that the Sun produces via the CNO fusion cycle while according to the Standard Solar Model this fraction constitutes 1.5% [1]. This limit was set just as a difference between the total energy release in the Sun found from the luminosity and the one generated in a hydrogen sequence alone, found from the fluxes of solar neutrinos measured in solar neutrino experiments [2] hence it is more like the limit of the non-hydrogen sequence source of energy. Here it is taken into account the effect from neutrino oscillations with the oscillation

parameters of the MSW LMA region found in solar neutrino experiments and KamLAND [5].

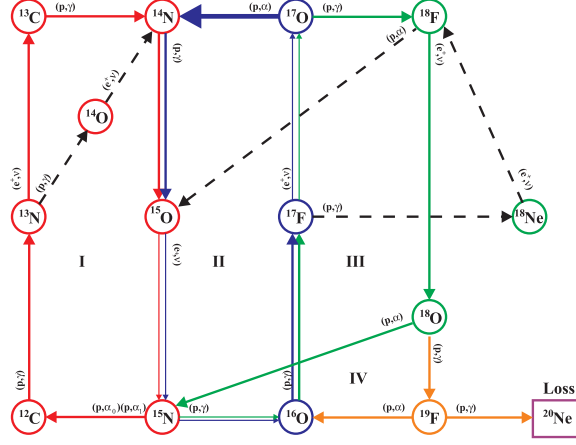


Figure 1: The scheme of CNO reactions.

In a next few years even in the optimistic scenario of the real progress with the solar neutrino experiments it will be hardly possible to decrease this limit lower than 5% [4] utilizing only the data on a hydrogen sequence neutrinos because it will be hardly possible to reach the accuracy in the measurements of these neutrinos less than 5%. Lithium experiment has a potential to confirm or reject the value 1.5% predicted by the standard solar model. For a certain energy release in CNO cycle there should be a corresponding surplus from  $^{13}\text{N}$ - and  $^{15}\text{O}$ -neutrinos to the total rate expected from the fluxes of neutrinos generated

Table 1. Standard Model Predictions (BP2000): solar neutrino fluxes and neutrino capture rates, with  $1\sigma$  uncertainties from all sources (combined quadratically).

Source	Flux ( $10^{10}\text{cm}^{-2}\text{s}^{-1}$ )	Cl (SNU)	Ga (SNU)	Li (SNU)
pp	$5.95(1.00^{+0.01}_{-0.01})$	0.0	69.7	0.0
pep	$1.40 \times 10^{-2}(1.00^{+0.015}_{-0.015})$	0.22	2.8	9.2
hep	$9.3 \times 10^{-7}$	0.04	0.1	0.1
$^7\text{Be}$	$4.77 \times 10^{-1}(1.00^{+0.10}_{-0.10})$	1.15	34.2	9.1
$^8\text{B}$	$5.05 \times 10^{-4}(1.00^{+0.20}_{-0.16})$	5.76	12.1	19.7
$^{13}\text{N}$	$5.48 \times 10^{-2}(1.00^{+0.21}_{-0.17})$	0.09	3.4	2.3
$^{15}\text{O}$	$4.80 \times 10^{-2}(1.00^{+0.25}_{-0.19})$	0.33	5.5	11.8
$^{17}\text{F}$	$5.63 \times 10^{-4}(1.00^{+0.25}_{-0.25})$	0.0	0.1	0.1
Total		$7.6^{+1.3}_{-1.1}$	$128^{+9}_{-7}$	$52.3^{+6.5}_{-6.0}$

in a hydrogen sequence alone. The data presented in Table 1 show the rates calculated by the Standard Solar Model [7] for different neutrino sources.

One can see from these data that  $1\sigma$  errors vary from 17% to 25% for  $^{13}\text{N}$ - and  $^{15}\text{O}$ -neutrinos close to  $1\sigma$  errors for boron neutrinos. However one should take into account that there's a correlation of the fluxes of boron and CNO-neutrinos as it was discussed in [8]. The substantial issue is that while the contribution of CNO-cycle to the solar energy is only 1.5%, the weight of neutrinos from CNO-cycle in the production rate of  $^7\text{Be}$  on  $^7\text{Li}$  is about 30%, see below. By the time a lithium experiment can start measurements basically all fluxes but CNO-neutrinos will be measured with relatively good accuracy and the question about sterile neutrinos will be cleared to a very small limit, if so. There can be some delay with the detection of pep-neutrinos, but the ratio of pep-neutrino flux to pp-neutrino flux is fixed to high accuracy [1] so it will not present a problem for the evaluation of the rate from neutrinos of a hydrogen sequence in a lithium experiment. The effect from solar neutrinos can be measured with very good accuracy this being a characteristic feature of a lithium target because the production rate is high and the cross-section is well known, see Table 1. This is a very rare and very useful combination for a solar neutrino experiment.

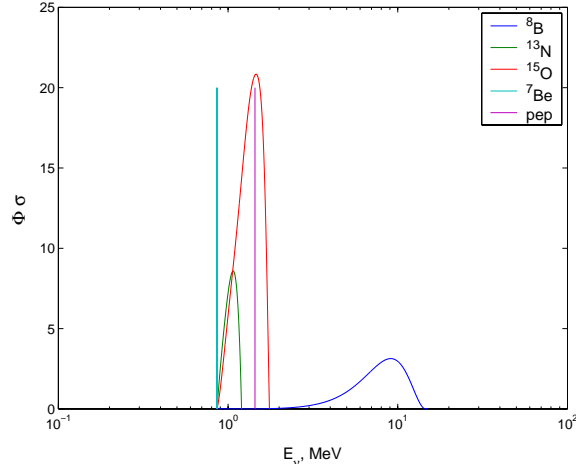


Figure 2: The sensitivity plot of lithium detector.

Figure 2 shows the sensitivity plot for a lithium detector [9], one can see that the contribution of the spectra of CNO neutrinos are quite substantial. The present discovery that MSW LMA region is responsible for the neutrino oscillations in the Sun means that approximately 1/2 of the neutrinos with the energy of about 1 MeV and 1/3 of boron neutrinos coming to the underground detector are of electron type. Then the total rate expected for a lithium target from solar neutrinos should be about 23 SNU including the predicted contribution from CNO-neutrinos about 7 SNU if to take that CNO cycle produces 1.5% of the total luminosity of the Sun. Here it is worth to note that for the present limit

7.3% the contribution to the rate of lithium detector from neutrinos of CNO-cycle will be 35 SNU, more than it is expected from neutrinos of a hydrogen sequence. This would be soon identified in the running experiment. Because lithium is a low atomic mass target (very high number of atoms in 1 g) and the abundance of  ${}^7\text{Li}$  in natural lithium is 93% even relatively small mass of lithium (10 tons) can provide high accuracy in the rate measurements. The statistics of a lithium experiment shows that for the effect of 20 SNU and 4 Runs per year having the total efficiency of the extraction 80% and the efficiency of counting 90% the statistical accuracy for 4 years of measurements should be about 3-4%. This is a very good number quite adequate to determine with good accuracy the contribution of CNO-neutrinos to the total rate. This will be the stringent test of the theory of stellar evolution and the termination of the long-standing goal – the neutrino spectroscopy of the interior of the Sun [1]. There's also a potential to increase the accuracy increasing the total mass of the target four-eight-fold by using several modules 10 tons each.

It is worth to note that even if the difference of the observed luminosity of the Sun and the estimated for the hydrogen sequence is established with good accuracy it does not provide a proof that the difference is due to CNO-cycle. The proof may be obtained from another balance - of the measured rates in a lithium detector. The most interesting thing would be to compare two values: first value is the contribution of the non-hydrogen sequence to the solar luminosity found as a difference of the observed luminosity of the Sun and the one found from the hydrogen sequence alone using the measured neutrino fluxes of the hydrogen sequence, and second value is the contribution to the solar luminosity of CNO-cycle found from the contribution to the measured rate in a lithium experiment neutrinos of CNO-cycle as a surplus to the rate determined by a hydrogen sequence. If there would be a substantial difference of these two values - there is some other source of energy in the Sun. To make this comparison both values should be known with good accuracy. As it was shown up the statistics of the planned lithium experiment enables to get the second value with good accuracy. What about the first one, the situation here is probably more complicated. Because the expected contribution of CNO-cycle to the solar luminosity is only 1.5% the accuracy in the neutrino flux measurements from a hydrogen sequence should be on the level of better than 1%. Obviously this level will be reached not soon. So for the nearest future one can talk only about the contribution of CNO cycle to the total energy production in the Sun found from a lithium experiment. In fact the interpretation of the results depends upon how accurately are measured the parameters of neutrino oscillations. One can expect that  $\Delta m_{12}^2$  will be found with very good accuracy by KamLAND in the nearest future. It is not clear yet how fast will be the progress with the determination of  $\Theta_{12}$ . If it will be found with a good accuracy one can investigate the energy balance

$$L_H(\Theta_{12}) + L_{CNO}(\Theta_{12}) = L_{\odot}$$

to look how accurate is this equality. If on the contrary the fluxes of the neutrinos of a hydrogen sequence and of CNO-cycle are measured with very good

accuracy while  $\Theta_{12}$  is not one can find  $\Theta_{12}$  as the value for which this equality is fulfilled. Both alternatives look attractive. But apparently this task is for the future when the flux of pp-neutrinos will be measured with the accuracy better than 1%.

A peculiar thing is that although lithium detector is a radiochemical one i.e. it measures the total rate from all the neutrino sources on the Sun, there's one possibility to find separately what is the contribution of  $^{13}\text{N}$  and  $^{15}\text{O}$  neutrinos. First of all one should note that for lithium detector the contribution of  $^{13}\text{N}$  neutrinos is 5 times smaller than that of  $^{15}\text{O}$  neutrinos, see Table 1. It helps in the interpretation of the results because the interference is small. But the spectra can be resolved! Let's look more in the details. If the fluxes of neutrinos from a hydrogen sequence are measured with very good accuracy then the only unknown thing is the energy of CNO cycle. But the energy generation in this cycle proceeds by two half-cycles: from  $^{12}\text{C}$  to  $^{14}\text{N}$  (first one) and from  $^{14}\text{N}$  to  $^{12}\text{C}$  (second one). The rates depend upon the abundance of  $^{12}\text{C}$  and  $^{14}\text{N}$  in the interior of the Sun.

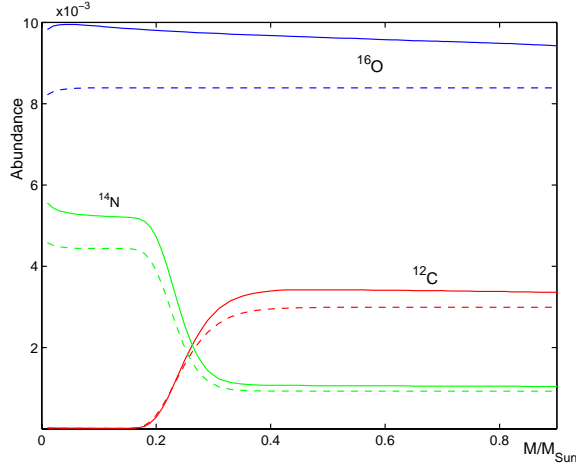


Figure 3: The distribution of the abundance of  $^{12}\text{C}$ ,  $^{14}\text{N}$ ,  $^{16}\text{O}$  along the profile of the Sun (in mass ratio units) in SSM with (solid) and without (dash) helium and metal diffusion [10].

Figure 3 shows the distribution of the abundance of  $^{12}\text{C}$  and  $^{14}\text{N}$  along the profile of the Sun (in a mass ratio units) [10]. One can see that the center of the Sun is depleted by  $^{12}\text{C}$  (it is burned out) while is enriched by  $^{14}\text{N}$  (it is accumulated). The question is: can this abundance distribution be confirmed by experiment? For the first half-cycle the energy release  $E_1 = ^{12}\text{C} + 2p \rightarrow ^{14}\text{N}$ . For the second one  $E_2 = ^{14}\text{N} + 2p \rightarrow ^{12}\text{C} + \alpha$ . The total energy release will be as it is well known  $E_1 + E_2 = 4p - \alpha$ . The energy released in the first half-cycle is a bit smaller than the one in the second half-cycle  $E_2 - E_1 = 2(^{14}\text{N} - ^{12}\text{C}) - \alpha$ . It is about 3.3 MeV. And if to take into account that the energy of neutrino emitted

in the first half-cycle is less than the energy of the neutrino in the second one, we obtain that in the first half-cycle the Sun gets less energy only by about 3.1 MeV than in the second half-cycle, this means that these energies are very close. What about the contribution to the rate of lithium detector, the situation here is very different. The contribution of the  $^{15}\text{O}$ -neutrino is 5 times bigger than the one of  $^{13}\text{N}$ -neutrino. Then a system of two equations can be written.

$$\begin{cases} L_H + L_{CN} + L_{NO} = L_{\odot} \\ R_H + R_{CN} + R_{NO} = R_{Li} \end{cases}$$

Here  $L$  – luminosity,  $R_{Li}$ ,  $R_H$  the measured and estimated for the hydrogen sequence rates in lithium detector,  $R_{CN}$  and  $R_{NO}$  means the rates from neutrino born from  $^{13}\text{N}$ - and  $^{15}\text{O}$ -decays,  $R = yL/4\pi R_{SUN}^2 \varepsilon$ , where  $R_{SUN}$  – the distance from Sun to Earth,  $\varepsilon$  is the energy contributed to the Sun per one neutrino emitted in each half-cycle of CNO-cycle and  $y$  – the capture rate per one neutrino of  $^{13}\text{N}$ - and  $^{15}\text{O}$ -spectra. One can see from these equations that principally it is possible to find separately the fluxes of  $^{13}\text{N}$  and  $^{15}\text{O}$  neutrinos. The only thing one should know are the fluxes of neutrinos from a hydrogen sequence and the parameters of neutrino oscillations. With good accuracy. And of course to measure the rate by lithium detector.

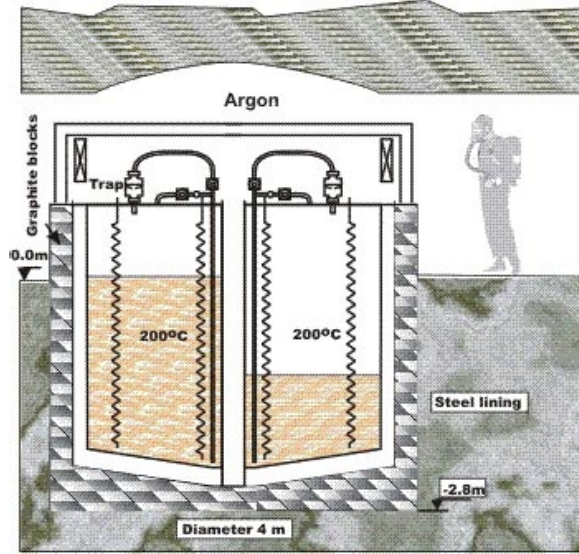


Figure 4: The scheme of lithium detector.

The technique of lithium experiment is now under development [11]. The detector itself can be made quite compact. Figure 4 shows the possible configuration of the detector with one module of 10 tons of metallic lithium in an underground chamber. One can see that the scale of the lithium installation is quite modest in comparison with other solar neutrino detectors. The difficult

point for a lithium project is the counting of  ${}^7\text{Be}$ . To have a good statistics the efficiency of the counting should be about 80-90%. But  ${}^7\text{Be}$  decays mainly to the ground state of  ${}^7\text{Li}$  through the electron capture and the energy of Auger electron is only 55 eV. It presents a big problem to measure such a small energy release when one should count single atoms during long time of measurements (100 days). The decay to the excited state of  ${}^7\text{Li}$  is accompanied with the gamma-ray of 478 keV which is a very convenient line for the detection, but the branching ratio of this mode is only 10%. The only technique which looks perspective for a full-scale lithium experiment is a cryogenic microcalorimetry. The principal possibility of using this technique for the counting of  ${}^7\text{Be}$  was shown in [12], [13], [14] but for the real technology of beryllium extraction from lithium and for the low background environment the appropriate scheme of the detector should be found and tested.

To summarize we should note that a lithium experiment has a good discovering potential in the study of solar neutrinos and the more accurate are the data on the neutrino fluxes from a hydrogen sequence and on the neutrino oscillation parameters, the more information on CNO-cycle one can obtain from the results of a lithium experiment. For a given accuracy of the measurements these results can be interpreted also in terms of the parameters of neutrino oscillations, or in terms of the balance violation in the energies produces in a hydrogen sequence plus CNO-cycle and the total solar luminosity this being an indication on the other possible source of solar energy. This work was supported in part by the Russian Fund of Basic Research, contract N 01-02-16167-A and by the Leading Russian Scientific School grant N 00-15-96632.

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